TITLE: Method for controlling light beam using adaptive micro-lens

Cross-references to related applications

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1. "Method for linearization of an actuator via force gradient modification", US Patent Application 09/813839, filed March 22, 2001.

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~~Statement Regarding Federally sponsored R&D~~

Not applicable

Reference to Microfiche Appendix

Not applicable

Field of the invention

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The invention pertains to optical communications and in particular to the control of optical light beams using adaptive optical elements.

Background of the invention

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The field of communications has benefited enormously from the introduction of optical communications technology. Fundamentally, this technology exploits the inherent bandwidth potential of the light itself as a carrier. As this technology matures, the need for the direct optical processing of the signals is becoming greater. Much of the communications infrastructure in operation in the field relies on signals being converted back to electrical for much of the processing and management. Direct optical processing has the benefit of avoiding the need for such conversion equipment with its associated costs, losses, and amplification requirements.

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One of the critical issues within the field of optical communications is centered on the situation when many optical signal channels on parallel fibers have to be controlled, adjusted, or switched at a single point in the communication system. This drives the need for a microelectronic device with a considerable level of device integration and individually adjustable channels. Simultaneously there is a clear need for devices that will perform these functions whilst being rapidly adjustable in operation. Candidate devices are expected to have low insertion losses and the lowest possible wavelength dependence.

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One of the fundamental building blocks of an optical communications system is the optical cross-connect or optical crossbar switch. These devices function to selectably connect any one of an array of incoming optical signals to any one of an array of outgoing channels. Inherently these devices consist of a multiplicity of optical communications channels that are often implemented on one semiconductor device wafer using micro-machining technology.

A variety of specific individual device structures have been proposed and fabricated to address this application. While many of these rely on non-linear optic materials to obtain switching actions, a very popular way to achieve this end at the time of this application for letters patent is by means of micro-electromechanical structures. These are usually micro-mirror devices that tilt, flex, or flip upon application of an appropriate control voltage.

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Most typically, these devices have two states, one of which causes an incoming beam of light to bypass the mirror, either by flipping the mirror down or removing it from the beam path by some other means, and a second position in which the mirror is interposed in the path of the beam so as to reflect it into some or other desired direction. This is done in order to couple the optical beam into an output channel, usually via a micro-lens and optical fiber arrangement.

The small apertures involved in the light-carrying cores of the optical fibers, particularly single mode fibers, lead to considerable beam divergence. This is typically addressed via suitably small micro-lenses that seek to collimate or focus the divergent light beam emerging from the input signal optical fiber. At the output end of the crossbar switch there is a concomitant requirement for a lens to ensure appropriate coupling to the output optical fiber. Again there are great constraints on the scope of the physical dimensions of these devices.

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A particular problem in these arrangements is the fact that the fixed nature of the micro-lenses restricts the latitude of design available to optical engineers. It also puts constraints on the silicon micro-machined optical switching devices that typically form

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the heart of these devices in that these devices have to be fabricated such that they are optically matched to the fixed lenses in order to ensure minimum insertion losses and to restrict losses inside the devices.

This restriction would be lifted if suitable adaptive micro-lenses were available. Since one of the very strengths of optical communications is the very wide bandwidth that it makes possible, there is every incentive to ensure that the optical devices and elements that are part of such a crossbar switch are commensurately fast, as this determines the rate at which routing and managed networking of the communication may be achieved. This issue applies not only to the sophisticated silicon devices in the crossbar switch, but also to any adaptive micro-lenses within such crossbar switches.

Liquid crystal lenses to address some of these issues are known in the art. However, these devices have limited speed due to the inherently slow switching speed of the liquid crystal mechanism. In a previous decade much collective effort was devoted to deformable macroscopic mirror devices for light projection systems, and in this respect piezoelectrically deformed lenses are known, but these clearly do not lend themselves to application in miniaturized optical crossbar switches.

Micro-electromechanical (MEMS) devices have been applied in the field of adaptive optical devices before and are attractive from the point of view of their relatively high switching speeds. However, MEMS devices are more typically employed as two state devices for binary functions, this being due to the difficulty in obtaining controlled analog deformation from the cantilever and torsion structures typically employed in these devices. Devices aimed at the controlled adaptation of light beams are therefore typically difficult to fabricate using typical prior art MEMS devices.

In respect it should be borne in mind that the user of an adaptive optical element would in general prefer to maintain the full dynamic range of adaptation while simultaneously demanding good control over that range, most particularly, at the low end of the adaptation range. The concern about this end of the range is due to the fact that there are many optical systems in where slight adaptation of focal lengths and the like, have greatly disproportionate resulting effects within the overall optical systems.

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Another semiconductor technology approach for obtaining adaptive optical elements is to employ a membrane that is fixed at its perimeter, or that extends over a system of holes, and to then deform one or more of these membranes using an electric field for electrostatic attraction. The typical device fabricated in this way is used to produce beam extinction or modulation by employing very tiny deformations and the principle of optical interference. Along with these general principles of operation, comes a general tendency of these devices to be inherently wavelength-sensitive.

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Some of the objects of the present invention include:

1. to present a method by which a wide range of adaptive optical refraction may be produced with good accuracy and reproducibility,
2. to ensure optical beam refraction with a reproducible zero-voltage state,
3. to obtain optical refraction that is both rapidly adjustable,
4. to provide a means to obtain a fixed degree of refraction when the wavelength is changed,
5. to provide a method by which the objects may be attained in a miniaturizable device,

6. to provide a method to ensure that the above objects are attained in a manner that is compatible with the requirements of micro-machined optical crossbar switches, and

7. to ensure the integration of such high-speed adaptive lenses in order to allow their incorporation into miniaturized multi-channel optical devices.

Brief Summary of the invention

Individual elements in a micro-electromechanical array of integrated stretched membrane devices are independently addressed and controlled to produce independently controlled degrees of refraction of light beams.

Brief Description of the Drawings

FIG. 1 shows a micro-electromechanical device in accordance with the present invention.

FIG. 2 shows a block diagram of the device in accordance with the present invention.

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Detailed D scription of th preferred embodiment

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FIG. 1 illustrates the essence of the preferred embodiment of the present invention as a micro-electromechanical (MEMS) adaptive lens. In practical application the complete device would have an array of elements of the type depicted here. For the sake of clarity, FIG. 1 shows a single element or channel.

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Referring now to FIG. 1, flexible transparent electrode 1 is fashioned from a transparent and conductive material on top of flexible insulating layer 2. In the present application for letters patent, the term transparent refers to the material being optically transparent to wavelengths in the ultra-violet, visible and infrared ranges, and the term conductive is used to describe electrical conductivity. The two layers are fashioned over a circular "pillbox" cavity in frame 3 of the MEMS device. The section of the two layers that is suspended over the cavity in frame 3 constitute what we shall refer to in this application for letters patent as the transparent membrane of the adaptive lens. Frame 3 represents the fixed member of the preferred embodiment of the present invention. Frame 3 may be fashioned from silicon, poly-silicon, or a variety of other micro-machining-compatible materials, including silicon nitride.

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In the preferred embodiment of the present invention, flexible transparent electrode 1 is composed of indium tin oxide, but in the general case the material employed for the transmitting function may be selected to suit the light being transmitted. It is also possible to employ transparent layers in the form of multi-layers, for example anti-reflection layers can be added on top of transparent conductive layer 1.

In the general case, when using a multi-layer structure, one layer may be dedicated and optimized for the electrode function while another layer serves to optimize the optical transmission. Conversely, it is possible to make the entire transparent membrane from one material that has the optical, electrical, and elastic properties that are required.

Flexible insulating transparent layer 2 is fashioned on top of frame 3. In the preferred embodiment of the present invention, it is preferred that the elastic properties of the flexible membrane be provided by flexible insulating transparent layer 2 in the form of a silicon nitride layer, which is optically transmissive at the wavelengths of concern, and that the electrode function be provided by the indium tin oxide layer constituting optically transparent conductive layer 1. This is due in part to the fact that indium tin oxide has superlative transmissive properties whilst being conductive, while silicon nitride is well established as a preferred material for flexible structures in MEMS devices due to its relatively better elastic properties.

The air space under flexible insulating transparent layer 2 is created using a sacrificial layer micro-machining process. Sacrificial layer techniques are well established in the microelectronics and micro-electromechanical systems (MEMS) fields and will not be detailed herewith. Transparent base electrode 6 is fashioned from a transparent conductive material such as indium tin oxide on top of transparent base 4 by standard deposition processes. Glass is the material of choice for the preferred embodiment of the present invention, which is directed at operating wavelengths of 1550 nm. Silicon of the appropriate purity may be employed as material for wavelengths greater than the band gap of silicon. In the general case the material is required to be transparent at the wavelength range of choice.

By fashioning flexible insulating transparent layer 2 from an insulating material such as silicon nitride, flexible insulating layer 2 ensures electrical isolation between electrode 1 and transparent base electrode 6 in those cases where the material employed for the transparent base for frame 3 is conductive, such as will be the case for silicon. The transparent membrane is therefore attached along its perimeter to the fixed member, frame 3, along its perimeter. It is to be noted that the perimeter referred to here is that of the transparent membrane as a whole, that is, the outer sections of layers 1 and 2 that are suspended over the cavity in frame3.

There are many variations on the generic processes for fabricating micro-machined devices such as the adaptive lens described in this preferred embodiment and variations upon it. A detailed description of a representative variant of this kind of processing of MEMS devices is given by Bifano et al in Optical engineering, Vol 36 (5), pp. 1354-1360 (May 1977).

Access hole 7 is formed in frame 3 for two purposes. Firstly it serves as vent for trapped air when the transparent membrane of the device flexes, and secondly, it is employed to inject a refractive liquid into the air space formed by the "pillbox" cavity in frame 3. In the preferred embodiment of the present invention this refractive liquid is preferably optical immersion oil. In general the refractive liquid is chosen to have a high refractive index, a low vapor pressure and as low a viscosity as possible. Optical immersion oil satisfies these requirements.

During fabrication, those surfaces of the device that fall inside the pillbox "cavity", including transparent base electrode 6, are treated with an oleophobic material such as the low surface energy coatings employed as standard practice in MEMS fabrication to

counter the well-known stiction problem. Since there is no preferential site for an injected oil droplet under these circumstances, the oil droplet localizes itself in the middle of the pillbox and fills the "pillbox" to a degree determined by the droplet volume. The volume selected in the preferred embodiment of the present invention, is such that the droplet is conformal with both the central portion of the transparent membrane and with the transparent base electrode 6.

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The adaptive refractive function of the present invention is established by the combination of refractive liquid droplet 5, flexible insulating transparent layer 2, flexible transparent electrode 1, transparent base electrode 5, and transparent base 4. In this application for letters patent, we refer to the combination of transparent base electrode 6 and the transparent base 4 as the transparent flat. The refractive liquid droplet therefore combines with the transparent membrane and the transparent flat to create an adaptive lens. The transparent membrane separates two refractive regions of differing refractive index. In the case of the preferred embodiment of the present invention, the two regions are air and optical immersion oil. In the general case, it can be a wide selection of substances and it is specifically possible to implement the present invention with any fluid on one of the two sides of the membrane. In this application for letters patent the term refractive region is therefore used to describe any body of material, gas, liquid, or other substance with a refractive index, specifically including free space and vacuum.

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It is evident that these processes may be used to create alternative detailed embodiments of the current invention that allow fabrication by planar processing in which all devices are fashioned within deposited layers, rather than etching the frame 3 of FIG. 1.

With no voltage applied between electrodes 1 and 6, light beam 10 from light source 9, collimated or focused by fixed focal length lens 8, impinges on the flat surface of the transparent membrane and is transmitted directly through the combination of refractive liquid droplet 5, flexible insulating transparent layer 2, flexible transparent electrode 1, transparent base electrode 5, and optically transparent base 4 without any focusing.

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In FIG.1 light beam 10 is shown as focused by lens 8. Application of a voltage difference between electrodes 1 and 6 causes an electrostatic attractive force between the two electrodes 6 and 1. This is a standard actuating technique employed in many MEMS devices. In the case of the preferred embodiment of the present invention, as shown in FIG.1, this electrostatic attractive force results in the transparent membrane deforming substantially concavely in radially symmetrical fashion. This deformation is shown exaggerated in FIG.1 for the sake of clarity.

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This deformation causes light beam 6 to be refracted, and change focus as the adaptive lens assumes the shape of a half-concave lens and acquires a distinct negative focal length that becomes shorter with increasing applied voltage. In the preferred embodiment of the present invention, as shown in FIG. 1, this has the effect of diverging light beam 10 in opposition to the convergent effect of fixed focal length lens 8. As the voltage is increased, the refractive diverging effect of the adaptive lens increases.

Bifano et al, in FIG. 10 of Optical Engineering, Vol 36 (5), pp. 1354-1360 (May 1977), describe the variation of the membrane deformation with applied voltage in the absence of the refractive liquid droplet . It is evident from that work that the deformed membrane lends itself to good control at low applied voltages, which correlate to small deformations and low attenuation.

It is well known to practitioners in the field that layers such as flexible insulating transparent layer 2 and flexible transparent electrode 1 may be deposited with various degrees of pre-stress by an appropriate choice of micro-lithographic materials and processing conditions. In the preferred embodiment of the invention shown in FIG. 1 the flexible insulating transparent layer 2 and flexible transparent electrode 1 are preferably deposited in tension.

The purpose of this pre-stressing step is to obtain a radially symmetrical stress-field in the transparent membrane. This pre-stressing ensures that the transparent membrane is as flat as possible when no voltage is applied between electrodes 1 and 6. This in turn ensures that, at zero induced refraction, the device will transmit light beam 10 with the least change in direction.

This is an important requirement for adaptive lenses that are to function at the low-end of the adaptation range. The pre-stressing also provides the device with better control over membrane displacement, particularly at low voltages and small displacements. It furthermore ensures a high natural resonance frequency, which allows the device to be employed in systems that require rapidly varying adaptation.

In the case of the present invention, the stressed circular transparent membrane has a distinctive and well-controllable elastic deformation. MEMS devices are well known to exhibit a so-called "snap-down" phenomenon. This occurs in cantilever devices where the voltage reaches a point at which the elastic restoring force of the cantilever is exceeded by the electrostatic attractive force and the cantilever physically snaps down onto the silicon substrate. The present invention, by virtue of the choice of circular

membrane and pre-stressing, exhibits a deformation of the transparent membrane that is both radially symmetrical and much more controllable than cantilever devices. The choice of membrane materials, thickness and pre-stressing jointly determine the extent of depression of the center of the membrane for a given applied voltage.

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The elastic deformation of the transparent membrane is substantially concave with the detailed functional shape being determined by the diameter of the transparent membrane, the lateral extent of electrode 6, the elastic properties of the membrane, and the size of the applied voltage.

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The particular choice of employing a pre-stressed circular transparent membrane addresses in particular the matter of the efficacy of the technique presented here in the case of applications requiring low degrees of refraction. In such cases the deformation of the transparent membrane is extremely small and yet has to be controlled.

MEMS cantilever devices inherently deform or curl due to deposition-induced stresses. It is exceedingly difficult to produce cantilever devices that are totally flat at zero applied voltage. Similarly, it is very difficult to impose a repeatable degree of curl on such a cantilever device with a view to having a repeatable zero-voltage curl.

In the case of devices that have deforming surfaces that are strapped down around their perimeters, but in which the deforming surface is not pre-stressed, there is also difficulty in assuring a repeatable situation at zero applied voltage. In keeping with the objects of the present invention, the deformable membrane is radially stressed in order to ensure a reproducible zero-voltage state for the device.

Another object of the invention is to ensure that optimal control over the deformation is obtained, particularly at small deformations. With devices that are not pre-stressed, the deformable membrane can assume a variety of deformations under the action of the voltage and the attenuation will thereby be difficult to control. By pre-stressing the membrane, the device is effectively being biased towards maximal optical throughput and minimum lens effect at zero applied voltage.

By way of example, a silicon nitride membrane with a diameter of 1mm, a thickness of less than one micron and an air gap of about 1.5 microns can be deflected about 1 micron with a voltage of below 100V. Such a membrane, together with a refractive liquid in the form of an oil with a refractive index of 1.5, will form, when deflected, a lens with a negative focal length of about 60 mm. The approximate formula for the focal length, f, is given by:

$$f = (n - 1) \times (\text{membrane diameter})^2/(8 \times \text{deflection})$$

where n is the refractive index of the liquid and is typically between 1.3 and 2.

When this adaptive lens is coupled with a fixed lens of focal length 60 mm, the focal length of the combination may be varied from 60 mm to infinity in a continuous and repeatable manner in a few milliseconds.

The above embodiments share the same inventive method comprising the use of a stressed transparent membrane, attached by its perimeter to a fixed frame, and actuated by electrostatic force to effect the controlled refraction of an input light beam transiting through the device.

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In the more general case the perimeter of the membrane is not circular, but is of any smoothly varying two-dimensional shape. This allows the membrane to be pre-stressed without inducing areas of excessive local stress, such as will occur at sharp corners. One particular alternative embodiment, in this respect, is a structure that is substantially rectangular with rounded corners and which will, near the center of its extent, behave as a cylindrical lens. Such elements are important for use with light sources that have differing divergence in perpendicular directions, such as side-emitting semiconductor lasers.

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It is evident from the preferred embodiment of the present invention, that, since the device may be adjusted according to the light source used, the voltage on the device may be changed to compensate for the variation of refractive index with the wavelength of the source, thereby keeping focal lengths the same. The wavelength limitations involved pertain only to the choice of materials. This matter is in the hands of the designer of products embodying the invention and does not limit the invention itself in respect of wavelength.

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No feedback is employed in the preferred embodiment of the present invention, as the addition of such a function adds to the complexity and cost of the device. This should be seen against the background of one of the objects of the invention being to obtain a low cost device. However, feedback can be incorporated in an alternative embodiment of the present invention by a number of different means. These include capacitively measuring the membrane position or sampling the light going in and coming out and adjusting the applied voltage and consequent deformation based on this measurement.

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The actuation of the membrane may be linearized or given any desirable transfer function. The term linearization is used in this application for letters patent to describe any collection of steps or mechanisms that leads to the actuation behavior of the actuator being mathematically described by a set of linear equations. One way in which this may be achieved is by means of lookup tables relating the input actuation and output deformation of the membrane. A linearization look-up table can be included in a semiconductor memory structure, which may be incorporated on the same contiguous piece of silicon wafer as the adaptive lens itself. In a co-pending application for letters patent under the title "Method for linearization of an actuator via force gradient modification" (US serial number 09/813839) this kind of mechanism is described in detail and is hereby incorporated in full.

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FIG. 2 shows such an alternative embodiment of the present invention in which the preferred embodiment shown in FIG. 1, is incorporated as adaptive lens 12, with impinging light beam 10. This adaptive lens 12 can also be controlled via control signal 13 which is adapted by linearization module 17 and provided to the adaptive lens 12 as actuation signal 14. The deformation of the membrane of adaptive lens 12 is sensed by position sensing means 15, which provides linearization module 17 with a feedback signal 16. Input power 18, typically 5 VDC, 12 VDC, or 48 VDC, is provided to the whole system and power supply 19 uses this energy source to provide the linearization module 17, and thereby adaptive lens 12, with a higher voltage 20, which may typically be between 50 and 100 V. Linearization module 17 generates the actuation signal 14 as a voltage, typically 0-100V. The linearization module can be of the analog type or, preferably, digital with a lookup-table and programmable with an arbitrary transfer function. Such methods are well known in the art. For greater long-term stability a

feedback sensor 15 measures the actual position and/or performance of the adaptive lens 12 and further modifies the actuation signal 14.

FIG.1 shows one adaptive lens element with an associated light source and collimating lens. This embodiment of the present invention may be repeated in two dimensions in a plane to create an array of adaptive lenses. It is possible to fabricate all of these devices on a single contiguous section of silicon wafer using standard MEMS technology as described and referred to above. In this way it is therefore possible to generate one- or two-dimensional arrays of adaptive lenses for managing optical beams from a multiplicity of optical channels. Any or all of these may be implemented with the feedback and control mechanisms shown in FIG. 2 in order to ensure adequate control over the refraction process.

A number of different ways exist to combine these individual adaptive elements. In FIG 3 and FIG.4, two ways are shown in which such elements may be combined. For the sake of clarity combinations in only one direction are shown, but it will be clear to those skilled in the art, that the same principles may be applied to create two dimensional arrays. In both cases the numbering, for the sake of clarity, is the same as in FIG.1. In both FIG.3 and FIG. 4, use is made of a communal transparent base electrode 6. In the case of the embodiment shown in FIG.3, each element has its own refractive liquid droplet 5 in a dedicated "pillbox" structure, similar to FIG.1. However, in the case of the embodiment shown in FIG.4, all the elements in the array share a communal droplet of refractive liquid 5. The individual refractive lenses are formed by localized deformation of the droplet underneath a particular transparent membrane that is deformed by an applied voltage.

There has thus been outlined the important features of the invention in order that it may be better understood, and in order that the present contribution to the art may be better appreciated. Those skilled in the art will appreciate that the conception on which this disclosure is based may readily be utilized as a basis for the design of other apparatus for carrying out the several purposes of the invention. It is most important, therefore, that this disclosure be regarded as including such equivalent apparatus as do not depart from the spirit and scope of the invention.